INTEGRATING DIGITAL TWIN TECHNOLOGY FOR REAL TIME BLOCKAGE DETECTION IN WATER COOLED ELECTRONICS

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Thesis Defense

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OUTLINE

- Introduction
- Background
- Methodology
- Investigation 1
- Investigation 2
- Conclusion

INFLUENTIAL PUBLICATIONS IN THIS WORK

First Author:

- **Richard Hainey**, Braden Priddy, Kerry Sado, Austin R.J. Downey, Jamil Khan, H.J. Fought, Kristen Booth. 2024. "*Digital Shadow-Based Detection of Blockage Formation in Water-Cooled Power Electronics*". 2024, International Mechanical Engineering Congress & Exposition.

Co-author:

- Kerry, Sado, **Richard Hainey**, Jose Peralta, Austin Downey, Kristen Booth. 2023. "*Digital Twin Model for Predicting the Thermal Profile of Power Cables for Naval Shipboard Power Systems*". 2023, IEEE Electric Ship Technologies Symposium (ESTS).
- Braden Priddy, **Richard Hainey**, Tyler Deese, Austin R.J. Downey, Jamil Khan, Herbert L. Ginn, 2024, "*Real-Time Thermal Data Assimilation for Power Electronics at The Edge*". 2024, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

In Progress:

- Josiah Worch, **Richard Hainey**, Kerry Sado, Austin R.J. Downey, Jamil Khan, 2024 " **Journal paper title to be decided**", * Journal publication to be determined*

INTRODUCTION - WHAT IS A DIGITAL SHADOW VS A DIGITAL MODEL VS A DIGITAL TWIN?

Digital Model:

- No data transfer.
- Passive reflection of the physical system [PS].

Digital Shadow:

- Unidirectional data transfer.
- Cannot directly affect PS.

Digital Twin:

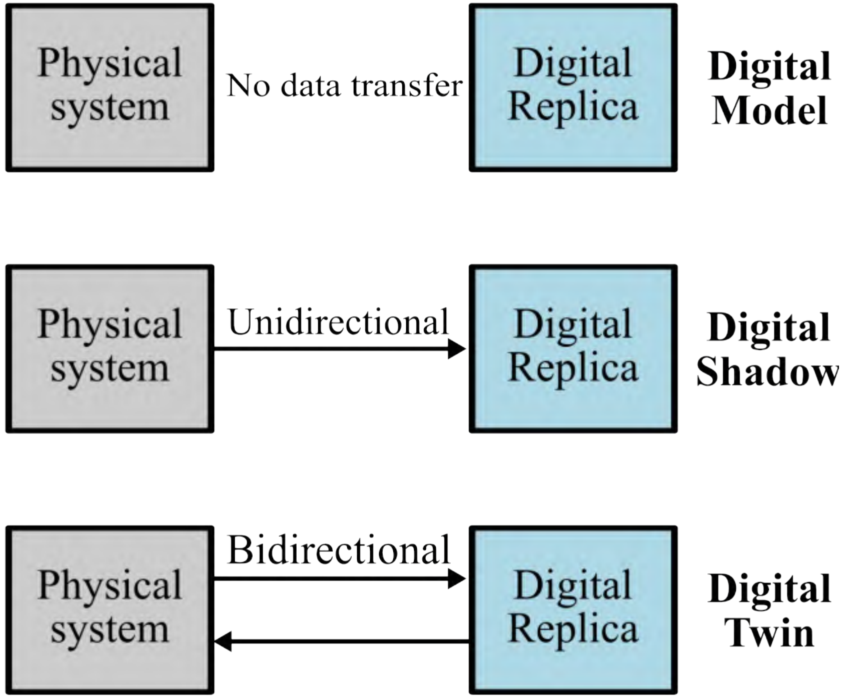
- Closed loop decision making.
- Bi-directional data transfer between models.
- Able to directly affect PS.

Data Transfer:

- Data transfer depends on if online or offline

Offline vs Online:

- Offline = no real time data transfer



K. Sado, J. Peskar, A. R. J. Downey, H. L. Ginn, R. Dougal and K. Booth, "Query-and-Response Digital Twin Framework using a Multi-domain, Multi-function Image Folio," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2024.3425276.

INTRODUCTION - DIGITAL SHADOW INTEGRATION

Physical Twin:

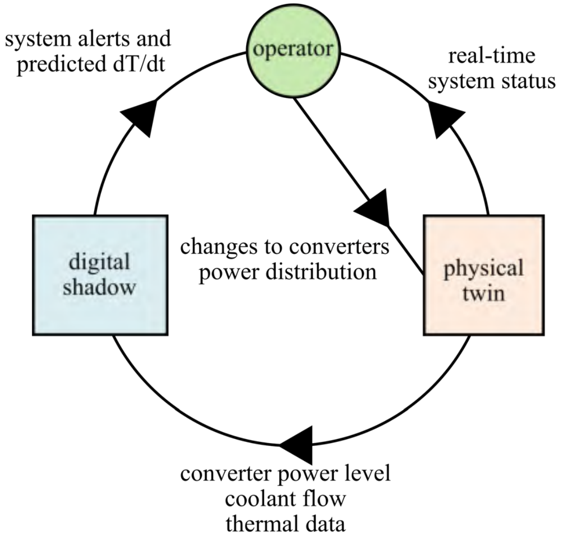
- Real world system.
- Experiments take place on.
- Provides information to digital shadow [DS].

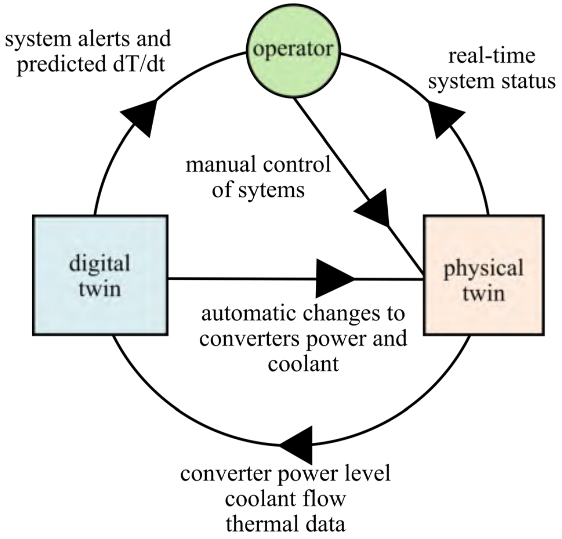
Digital Shadow:

- Digital representation of physical twin [PT].
- Calibrated off data from PT.
- Replicates conditions and aspects of PT.
- Provides a digital testbed for experiments that cannot be done to PT.
- Provides operator with system health projections.

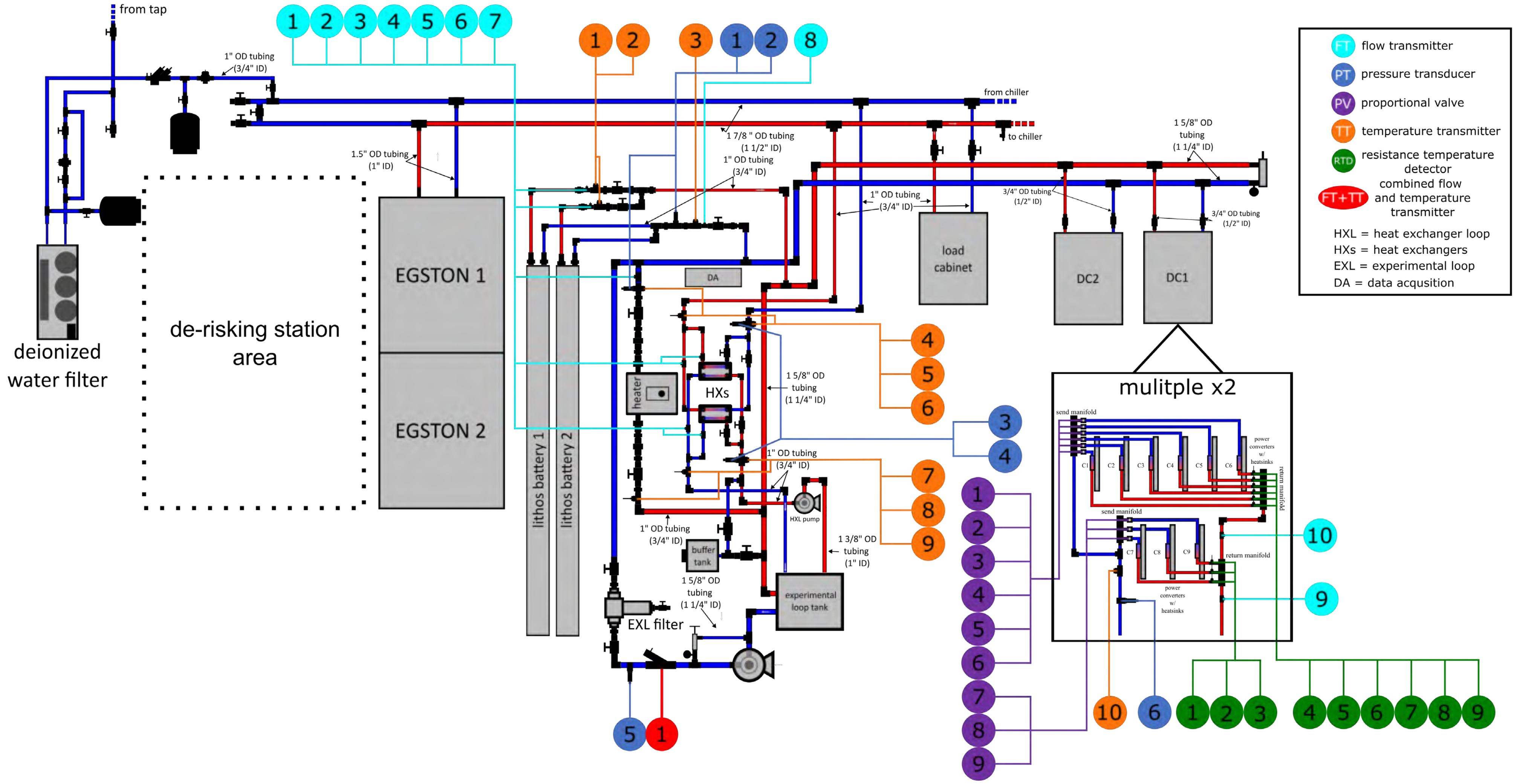
Operator:

- Provides initialization data to PT and DS.
- Receives health projections from DS.
- Observes current PT condition.
- Changes PT conditions based on information from DS.
- "Human in the loop"





BACKGROUND - SCEPTER LAB TESTBED OVERVIEW



BACKGROUND - WHY IS BLOCKAGE DETECTION IMPORTANT?

Blockage Formation Effect on Systems:

- Blockages in systems can lead to:
  - Underperformance of systems
  - Overheating issues
  - Overall degradation of component`s health and capability

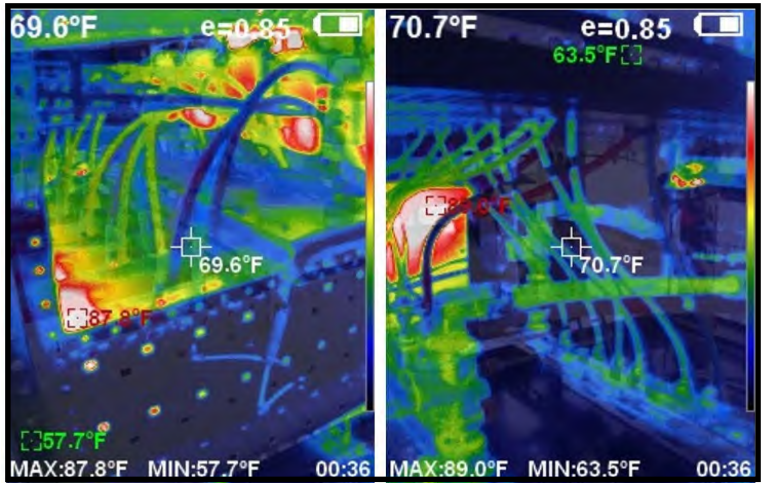
Effect of Blockage Formation:

- If left unchecked, issues can quickly result in potential system failure.
- System failures :
  - Crew habitation and comfort [e.g., HVAC]
  - Reduced engine power or engine failure resulting from fuel line or coolant line blockage.
  - Power electronics [e.g., radar array] failure resulting from coolant line blockage.

Preventive Maintenance:

- Vital that blockages are detected and dealt with before they become critical.

DDG 51 Arleigh Burke class destroyer. Military.com. (n.d.). https://www.military.com/equipment/ddg-51-arleigh-burke-class-destroyer



METHODLOGY - OVERVIEW OF BLOCKAGE DETECTION

Objective:

- Detect blockage formation within water cooled power electronic systems.
- Real-time temperature measurements from physical, real-world system in conjunction with a digital twin.

Approach:

- Using physical twin (PT) as a simulated representation of the real-world system – the digital twin (DT).
- Comparison of temperature similarity between models.
- Dissimilarity indicates blockage formation.

Importance:

- Vital to maintaining the continued operational capacity of a ship`s systems.

DDG 51 Arleigh Burke class destroyer. Military.com. (n.d.). https://www.military.com/equipment/ddg-51-arleigh-burke-class-destroyer

METHODLOGY - METHOD OF BLOCKAGE DETECTION

How:

- Implement digital shadow onto real word physical system in conjunction with a digital model.
- Blockage detection and thermal prediction accomplished through use of digital shadow system.
- Digital model designed using MATLAB Simscape.
- Use of offline 'batch' data from physical system feed into digital shadow.

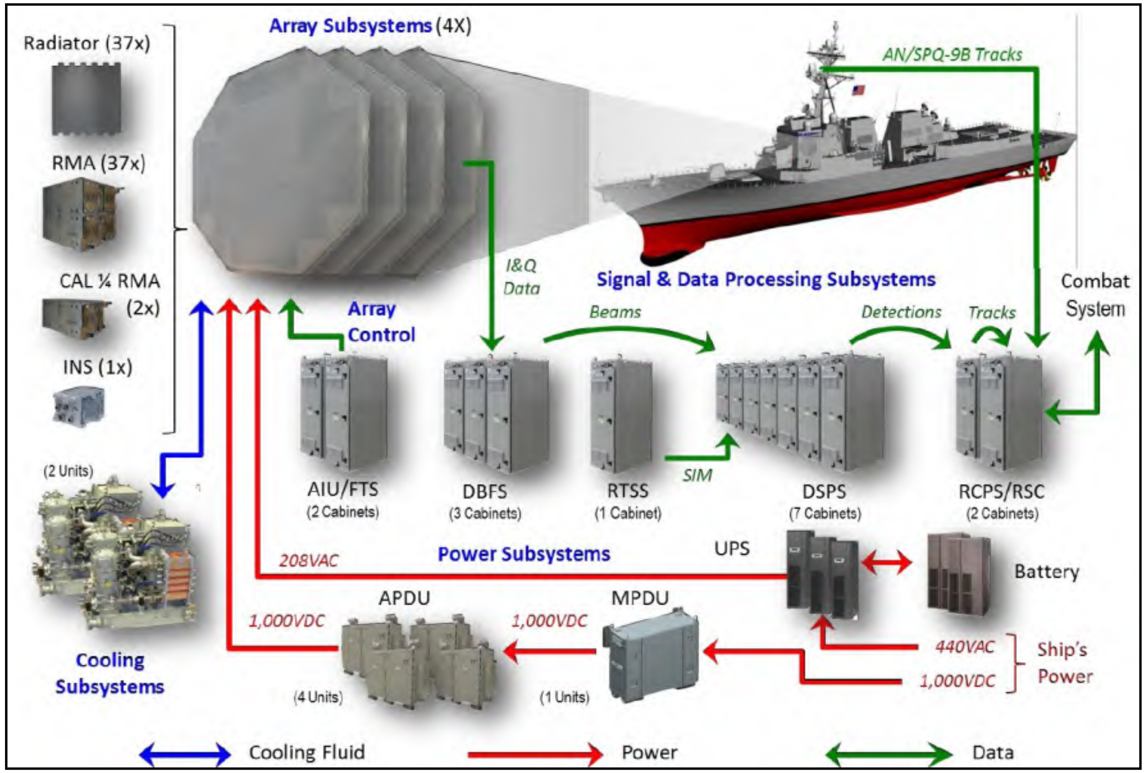
Offline Data Transfer:

- Offline = 'batch' data transfer.

Result:

- Effective emulation of physical system in digital environment where blockage detection.

MATLAB



[3] Ryan White, By, & White, R. (2021, February 25). *Report to U.S.Congress on U.S. Navy DDG-51 and DDG-1000 destroyers*. Naval Post- Naval News and Information. https://navalpost.com/report-to-congress-on-ddg-51-ddg1000-usnavy/

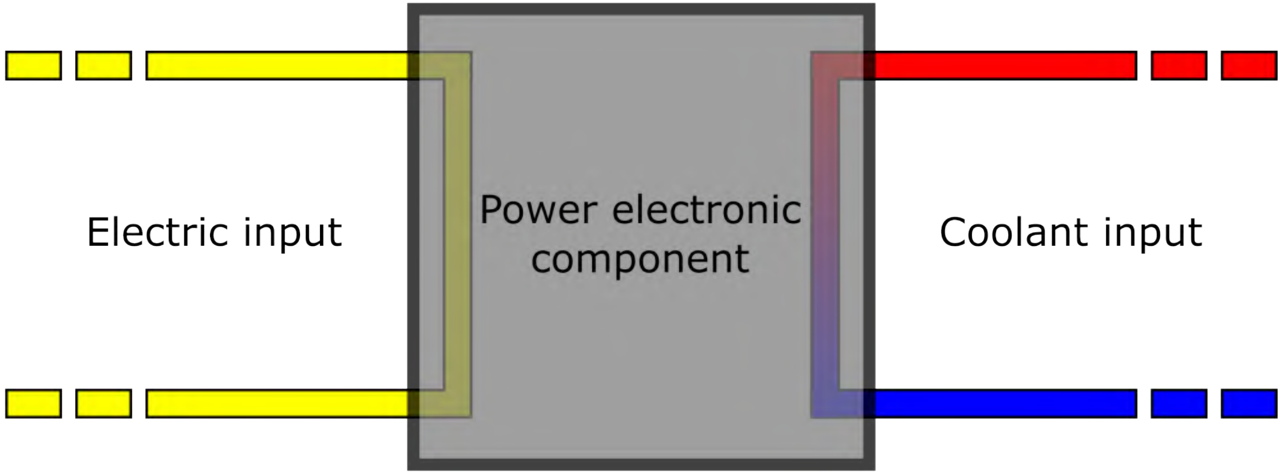
METHODOLOGY - BLOCKAGE EFFECT AND METHOD OF DETECTION

Effect on System and Components:

- Decreased coolant flow and overheating issues of affected components.
- Worst case: Overall failure of the affected components or systems.

Method of Detection:

- Compare temperatures from a physical twin in conjunction with a digital model with real-time controller [cRIO].
- Dissimilarity between physical and digital models indicates potential blockage formation.
- Uses several triggers to decrease possibility of false positives.
- Model gives an early warning to operators.



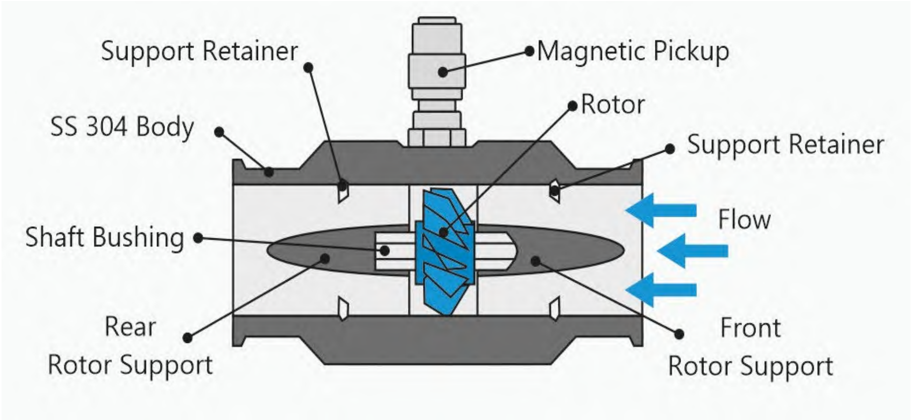
METHODLOGY - WHY NOT USE A FLOW TRANSMITTER?

Benefits of Temperature Sensors:

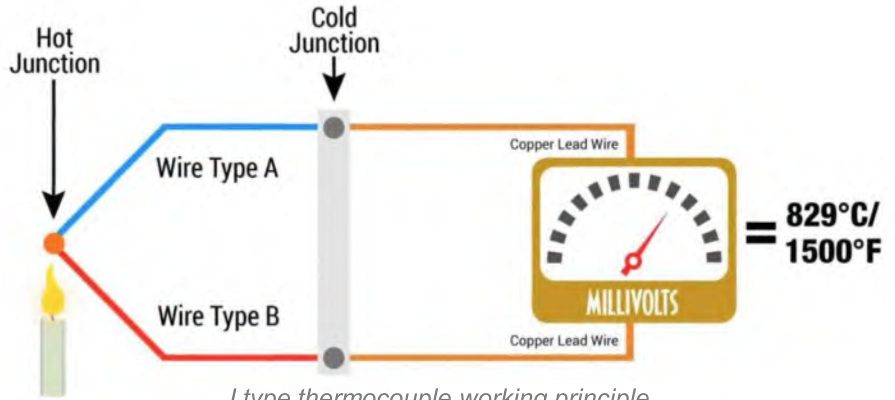
- Relatively inexpensive.
- Induces less flow restriction.
- Often preinstalled to liquid cooled electronics.
- Easier to preform maintain or replace.

Drawbacks of Flow Transmitters:

- Require more and involved frequent maintenance.
- More restrictive space requirements.
- Transmitter [turbine models] impellers prone to jamming and damage from debris.
- Expensive.



Turbine flow transmitter cross section
https://en.enelsan.com/data-base/how-turbine-flow-meter-works



J type thermocouple working principle
MIL-DTL-26482 Series 2 Thermocouple Contacts | MILNEC

DIGITAL SHADOW-BASED DETECTION OF BLOCKAGE FORMATION IN WATER-COOLED ELECTRONICS

Richard Hainey[1]. Braden Priddy[1], Kerry Sado[2], Austin R.J. Downey[1,3,*], Jamil Khan[1], H.J. Fought [2], Kristen Booth[2]

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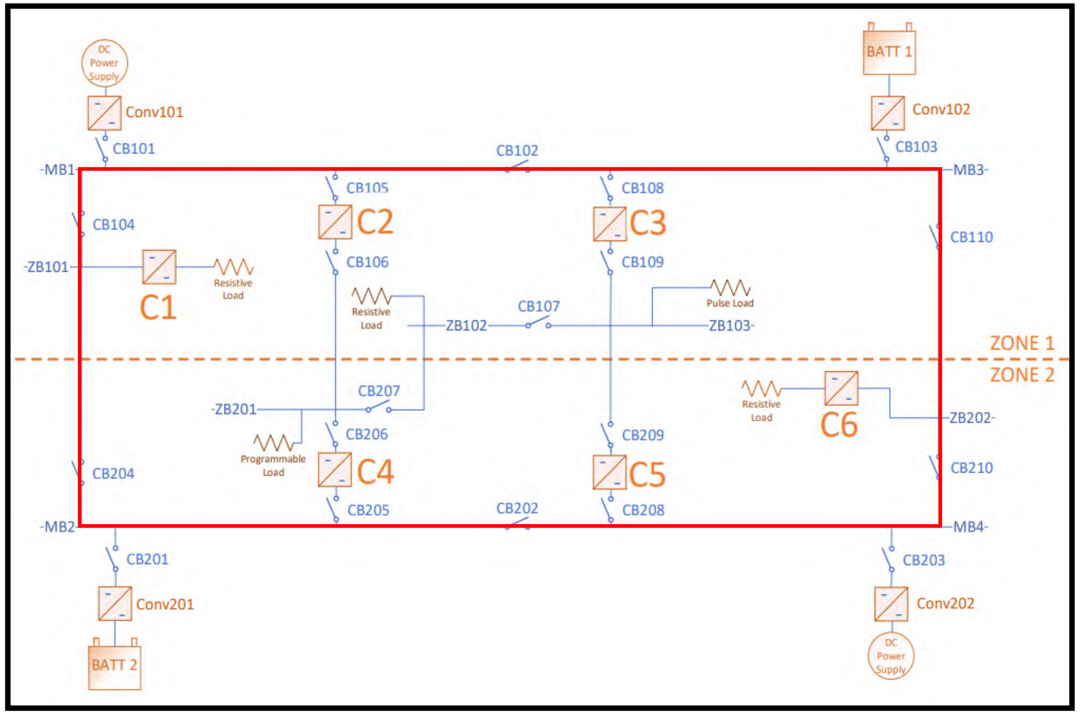
INVESTIGATION 1 - ELECTRICAL NETWORK FOR SCEPTER LAB TESTBED

Power Converters:

- Set of Six.
- Receives power from generator and batteries.
- Act as “Buck” and “Boost” DC power transformers.
- Boost converters supply power to major systems.
- Buck converters supply power to minor systems.
- Work in conjunction with other electrical system to create a microgrid emulator of ship`s systems.
- Examples: propulsion, energy weapons, radar, etc.

Waste Heat:

- Produces waste heat due during operation.
- Water cooled for higher cooling capacity vs air.
- Example input electrical power: 2kW.
- Example efficiency ~95%
- Waste heat production: 190 W.



INVESTIGATION 1 - PHYSICAL TESTBED OVERVIEW

Assembly:

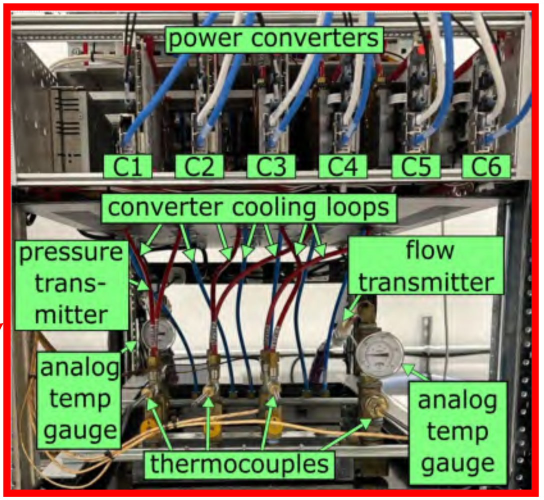
- Power converters.
- Coolant distribution manifolds.
- Temperature sensors.
- Flow gauges.
- Balancing valves.

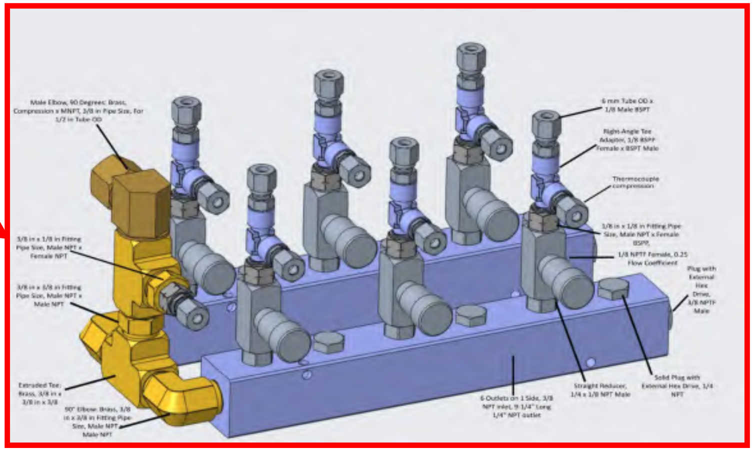
Sensors:

- Set of eight thermocouples:
  - ➢ Seven on return.
  - ➢ One on send.
- Records the change in temperature of coolant.

Flow Control:

- One proportional needle valve for each converter.
- Allows for flow balancing.
- Can perform experiments on individual converters.





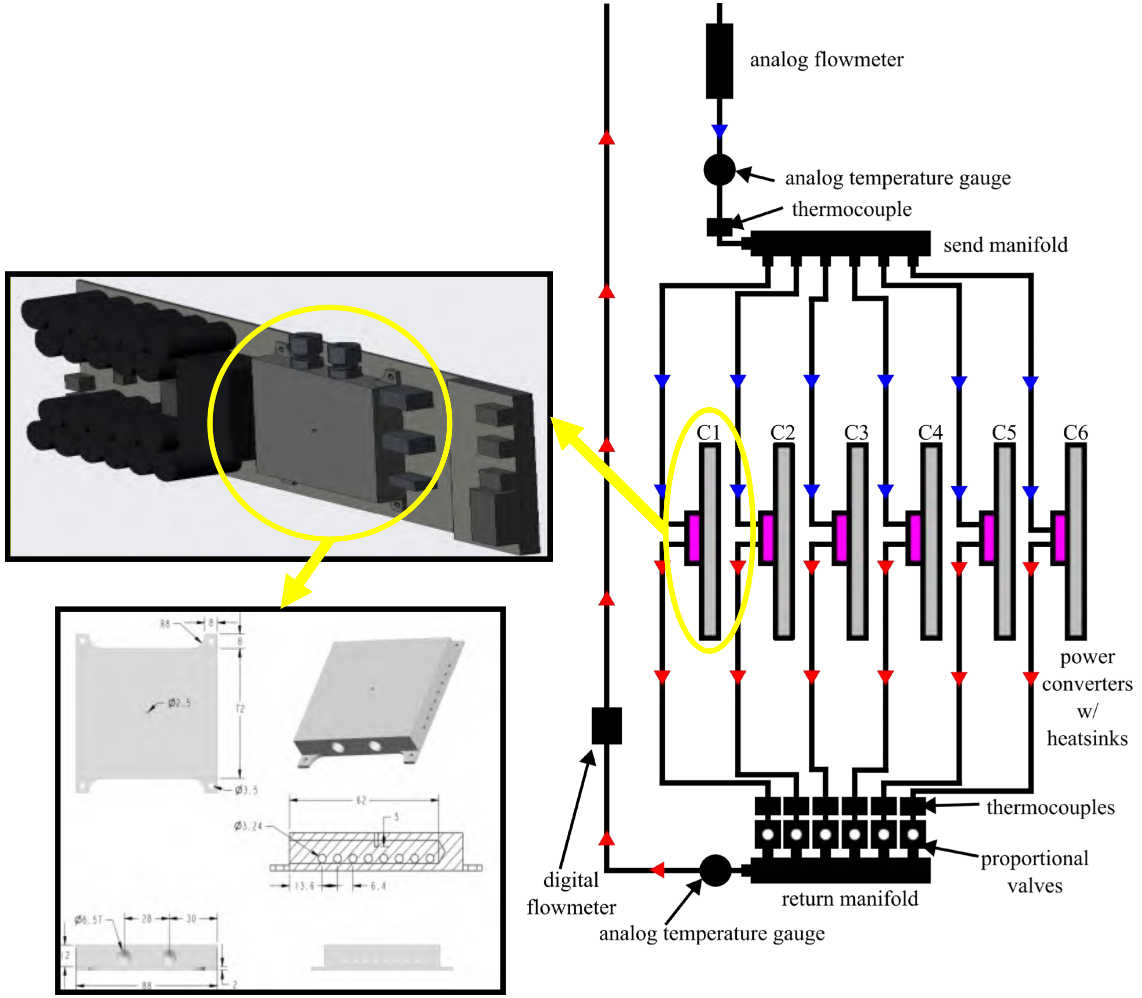
INVESTIGATION 1 - POWER CONVERTER COOLING DIAGRAM

Thermal Loop:

- Coolant moves through each loop for each converter, absorbing heat generated by semiconductor switching devices.
- Typical losses ~ 150 W per converter operating at full capacity.

Overheating of Power Converter:

- Safe operating temperature for power converters: up to 80°C (measured at heatsink).
- Automatic shutdown occurs if temperature exceeds 80°C.
- Operating above 80°C can damage the power converter and reduce its lifespan.
- Serious damage to the power converter and overall system may occur if overheating continues.



INVESTIGATION 1 - DIGITAL SHADOW SIMULATION

Purpose:

- The digital shadow identifies blockages early to mitigate risks of downtime or damage.

Detection:

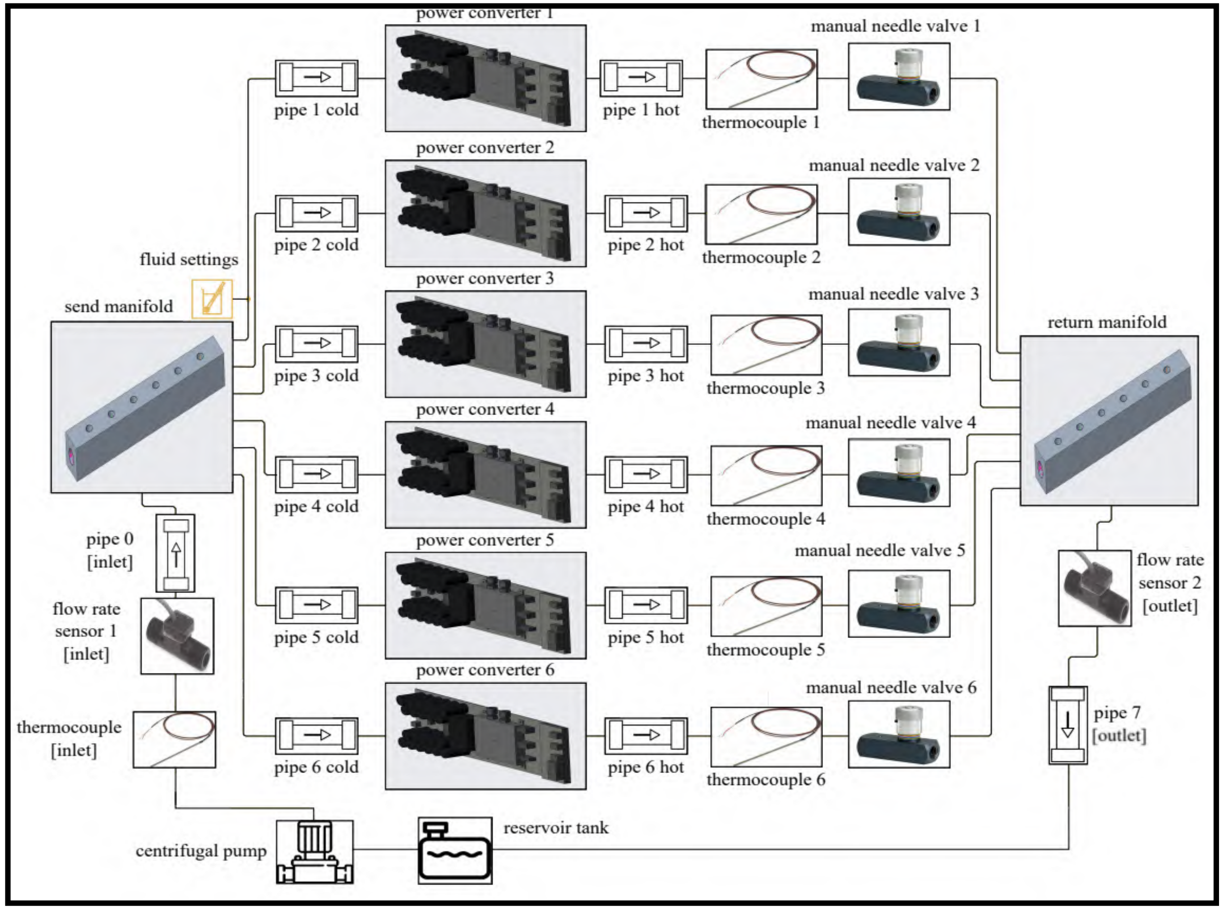
- Monitors abnormal temperature change rates (dT/dt); alerts operators if it exceeds a threshold.

Predictive Capability:

- Provides alerts on potential blockages before they become critical, maintaining safe thermal limits and converter reliability.

Integration:

- Integrates with the physical twin for informed decision-making.



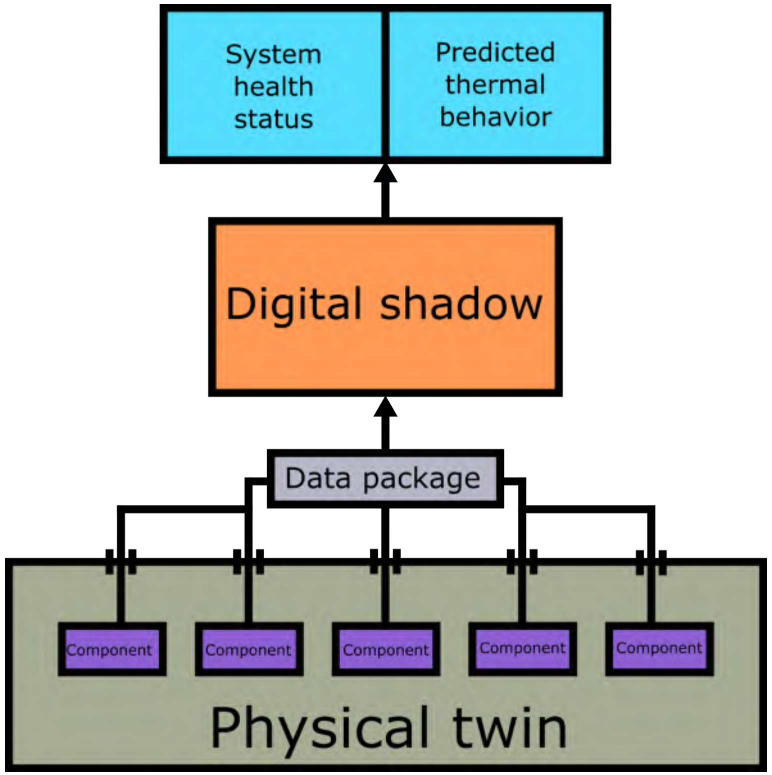
INVESTIGATION 1 - DIGITAL SHADOW CHARACTERIZATION AND CALIBRATION

Characterization:

- Digital shadow must accurately replicate the thermal behavior of the PT.
- Inaccurate digital shadow model = inaccurate thermal behavior prediction = Failure to find potential blockages in PT.

Calibration:

- Calibration drift over time affects accuracy of digital shadow.
- Periodic recalibration of the system must be done to maintain accurate emulator.
- Currently done manually but automatic optimization programs may be used – Particle swarm optimization (PSO).



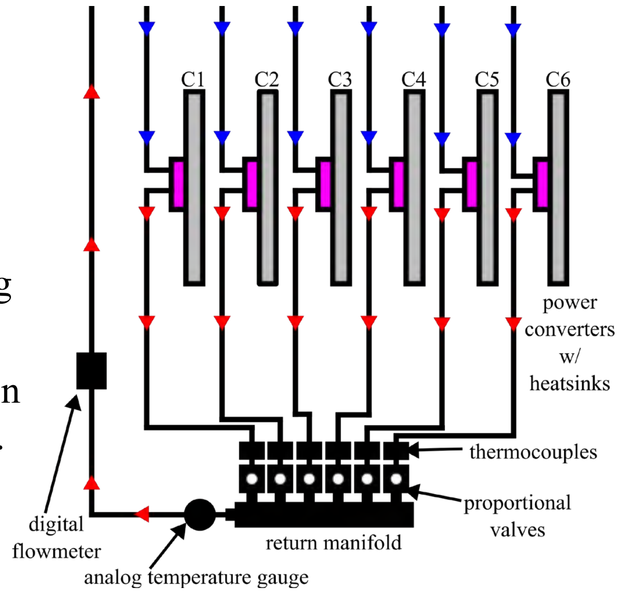
INVESTIGATION 1 - EXPERIMENT PROCEDURE AND DS CHARACTERIZATION

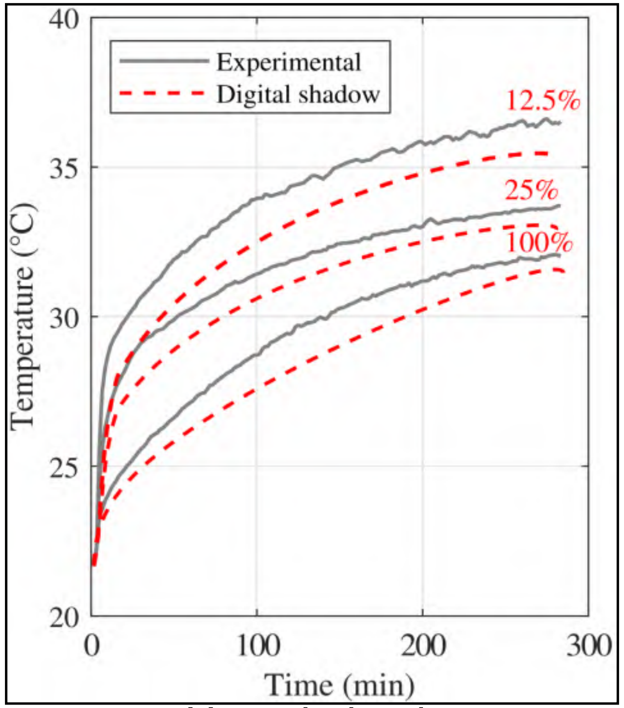
Purpose:

- Study effects of partial blockages on power converters under heat load.
- Determine temperature increase due to blockage in a single power converter.

Procedure:

- Simulated blockage by progressively reducing C2 valve opening by 12.5% over eight tests.
- Each test started with water coolant circulation at 2.46 lpm and ambient temperature of 22°C.
- C1, C2, C3, and C4 each supplied 2 kW; C1, C3, and C4 served as controls. C5 and C6 remained unpowered.
- C2's valve manipulated to simulate blockage.
- Testing lasted ~ five hours until reaching a quasi-steady state.
- Coolant temp returned to room temp before next valve reduction.





Unoptimized characterization results

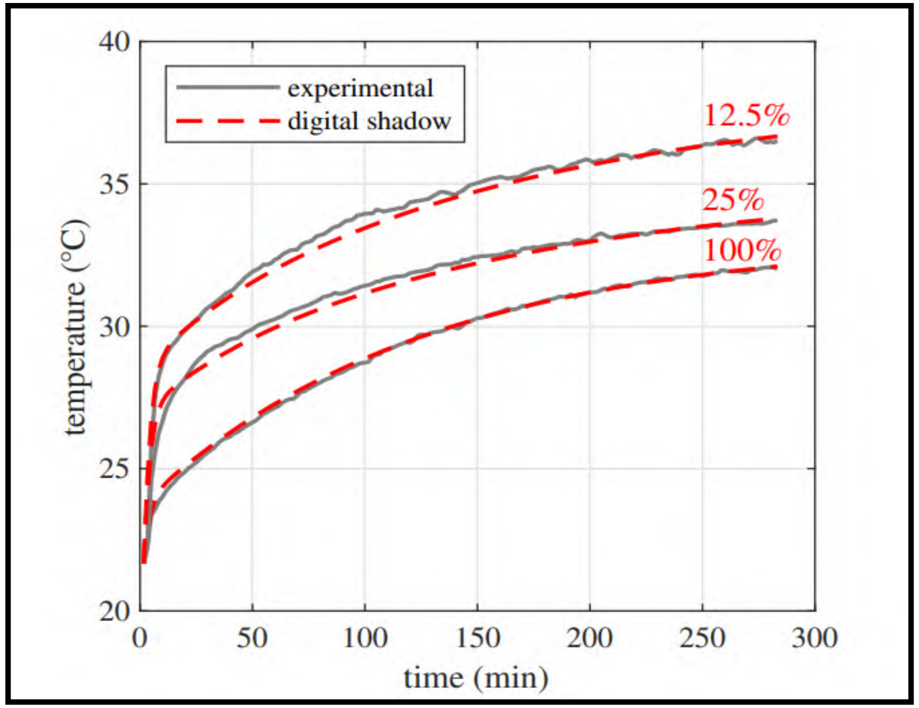
INVESTIGATION 1 - RESULTS: COMPARISON OF SIMULATION VS PHYSICAL TESTBED EXPERIMENTS

Experiment Overview:

- Results from reducing C2 converter valve opening from 100% to 12.5% at 2 kW.
- Lower percentages indicate increasing blockage.

Results:

- Simulation and physical tests show good agreement.
- Increased dT/dt and steady state as valve percentage decreases.
- Reduced cooling ability due to blockage formation resulting in loss of coolant flow.



INVESTIGATION 1 - RESULTS: BLOCKAGE FORMATION EFFECT ON HEATING BEHAVIOR

Temperature Change Analysis:

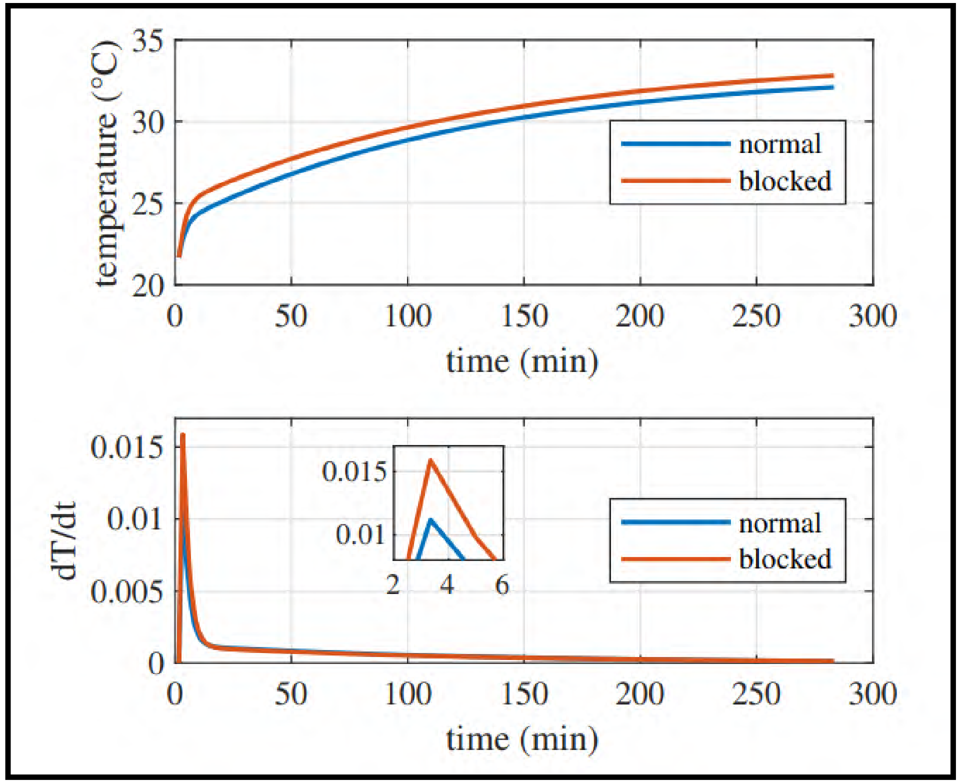
- Illustrates the abnormal rate of temperature change.
- Experimental data characterize normal dT/dt under operational conditions.
- Under no blockage, coolant temperature rises from ~22°C to ~24°C, reaching a steady state at ~33°C.
- With a 37.5% valve opening (blockage condition), temperature increases sharply to ~26°C, stabilizing at ~34°C.

Rate of Change:

- Maximum temperature spike under normal conditions: ~0.011°C/s.
- With 37.5% valve opening: ~0.0155°C/s, indicating blockage severity.

Result:

- Temperature increase is distinct enough to detect potential blockage formation.



DETECTION OF BLOCKAGE FORMATIONS WITHIN WATER COOLED ELECTRONICS USING DIGITAL TWINS

10/14/2024

Josiah Worch / Richard Hainey

UNIVERSITY OF South Carolina

Molinaroli College of Engineering and Computing

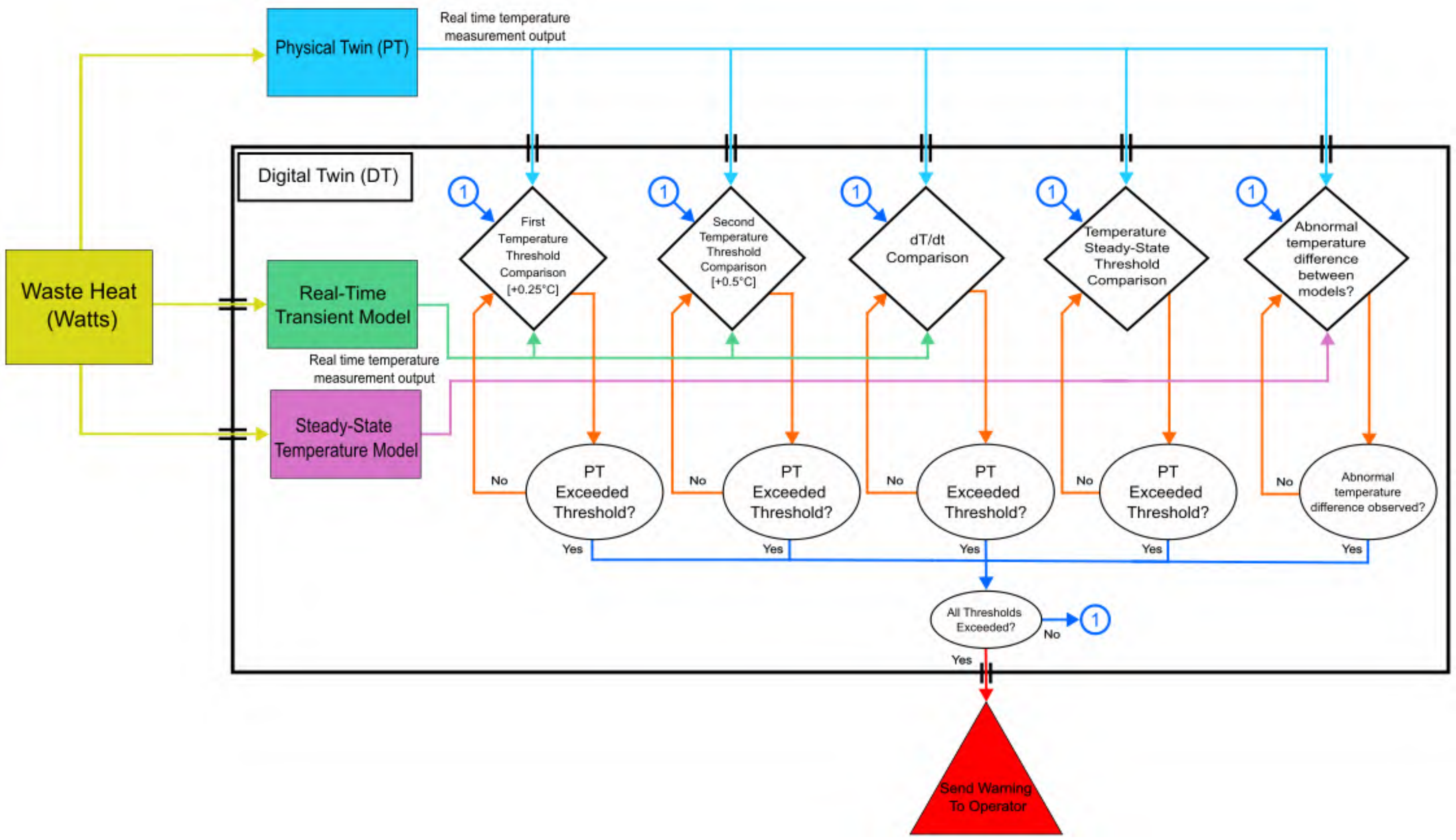
INVESTIGATION 2 - TESTBED SYSTEM OVERVIEW

BDPD:

"Blockage Detection and Power Distribution testbed"

Process:

- System provides waste heat wattage input for Physical Twin (PT) Emulation and Digital Twin (DT).
- Reads temp output from models.
- Compares PT data to DS data.
- Checks for heightened temperatures.
- Checks for abnormal temp change .
- If checks are triggered = potential blockage.
- Informs operator.



INVESTIGATION 2 - HEATING AND COOLING BEHAVIOR

Method of Blockage Detection:

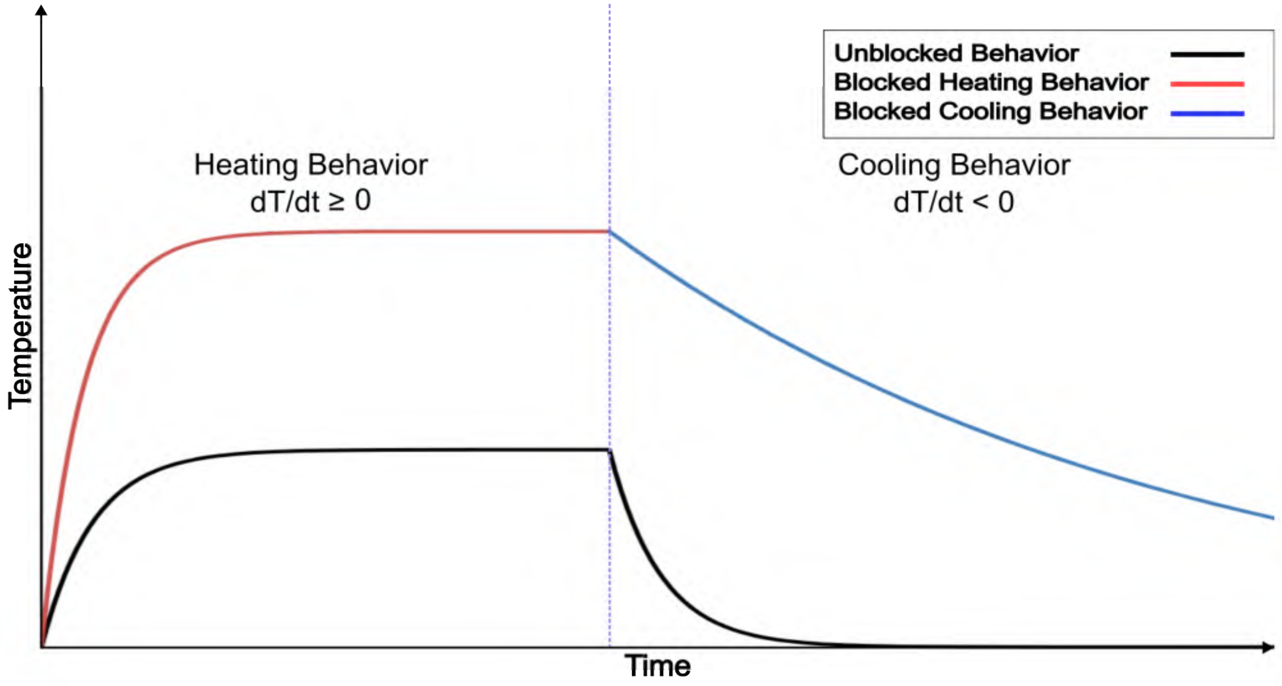
- Measure change in temperature over time (dT/dt).
- Measure steady state temperatures.

Heating:

- $[DT/dt]_{PT} > [DT/dt]_{normal}$.
- $[T]_{PT} > [T]_{normal}$.

Cooling / Lowering Heat Loss Power Profile:

- $[DT/dt]_{PT} < [DT/dt]_{normal}$.
- $[T]_{PT} > [T]_{normal}$.



INVESTIGATION 2 - EFFECT OF BLOCKAGE ON NEIGHBORING MODULES

Event:

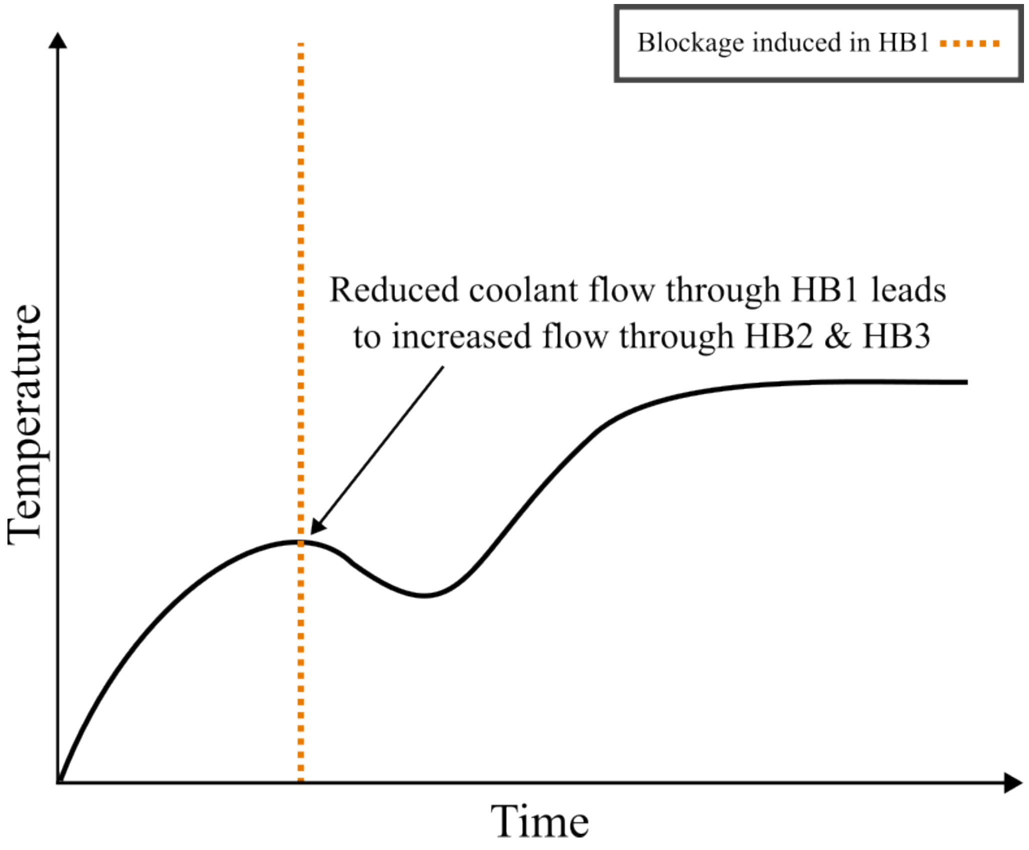
- Coolant flow to neighboring electronics increases when blockage forms in target electronic.

Effect:

- Results in increase heat transfer from neighboring units.
- Increased cooling = drop in temperature from transient model.

Importance:

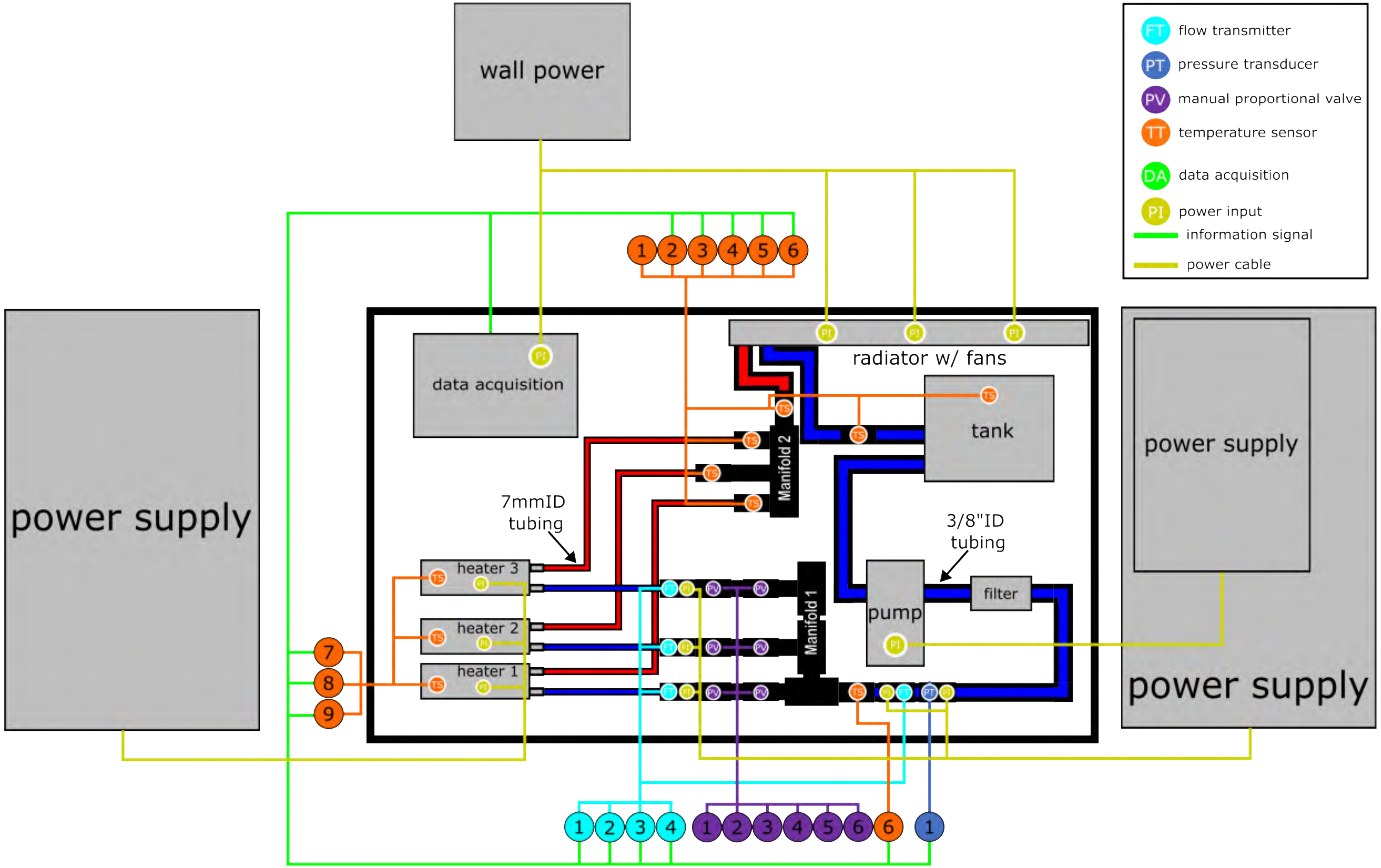
- Can be used as another trigger to determine blockage formation in system.



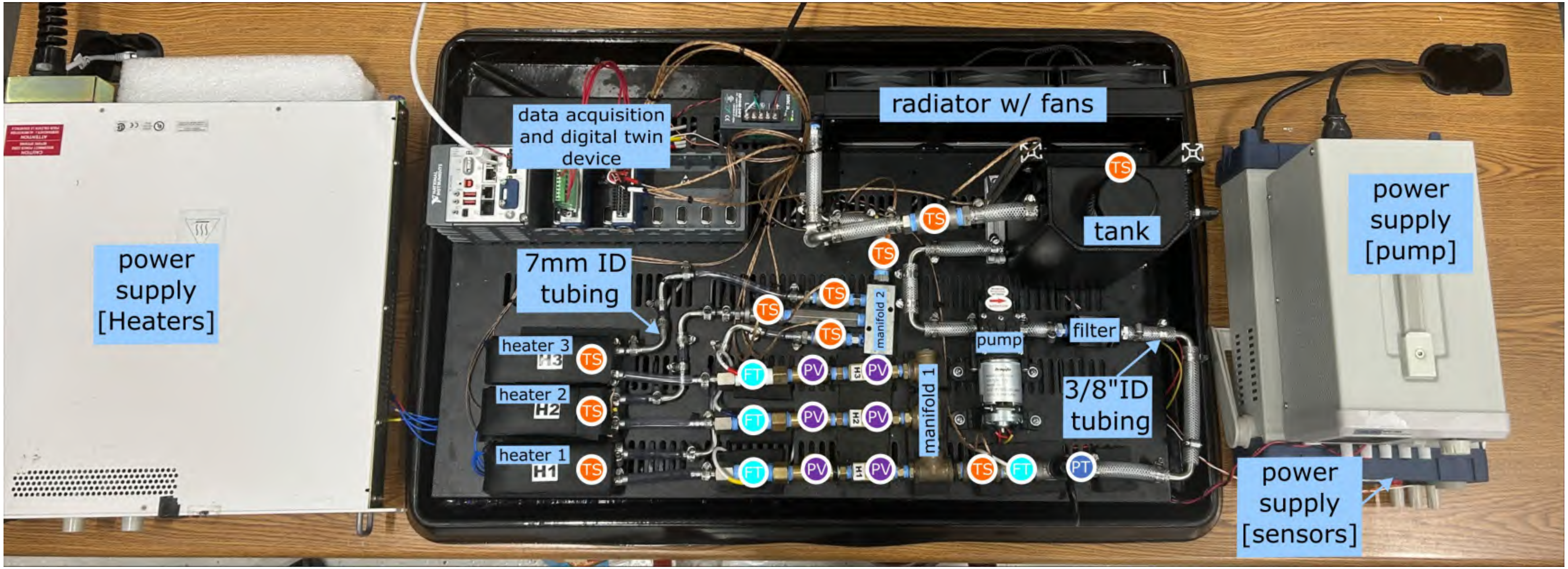
INVESTIGATION 2 - BDPD PHYSICAL TWIN TESTBED DIAGRAM

Physical Testbed:

- A physical testbed was designed and constructed to validate and calibrate the digital shadow.
- Includes proportional valves for simulation of blockage formation.



INVESTIGATION 2 - BDPD PHYSICAL TESTBED



INVESTIGATION 2 - INTERCONNECTION BETWEEN TWINS

Connection between PT and DT:

- Physical twin supplies cRIO information on load profile, and temperature responses from heater components.
- DT runs in real time on cRIO.

Input:

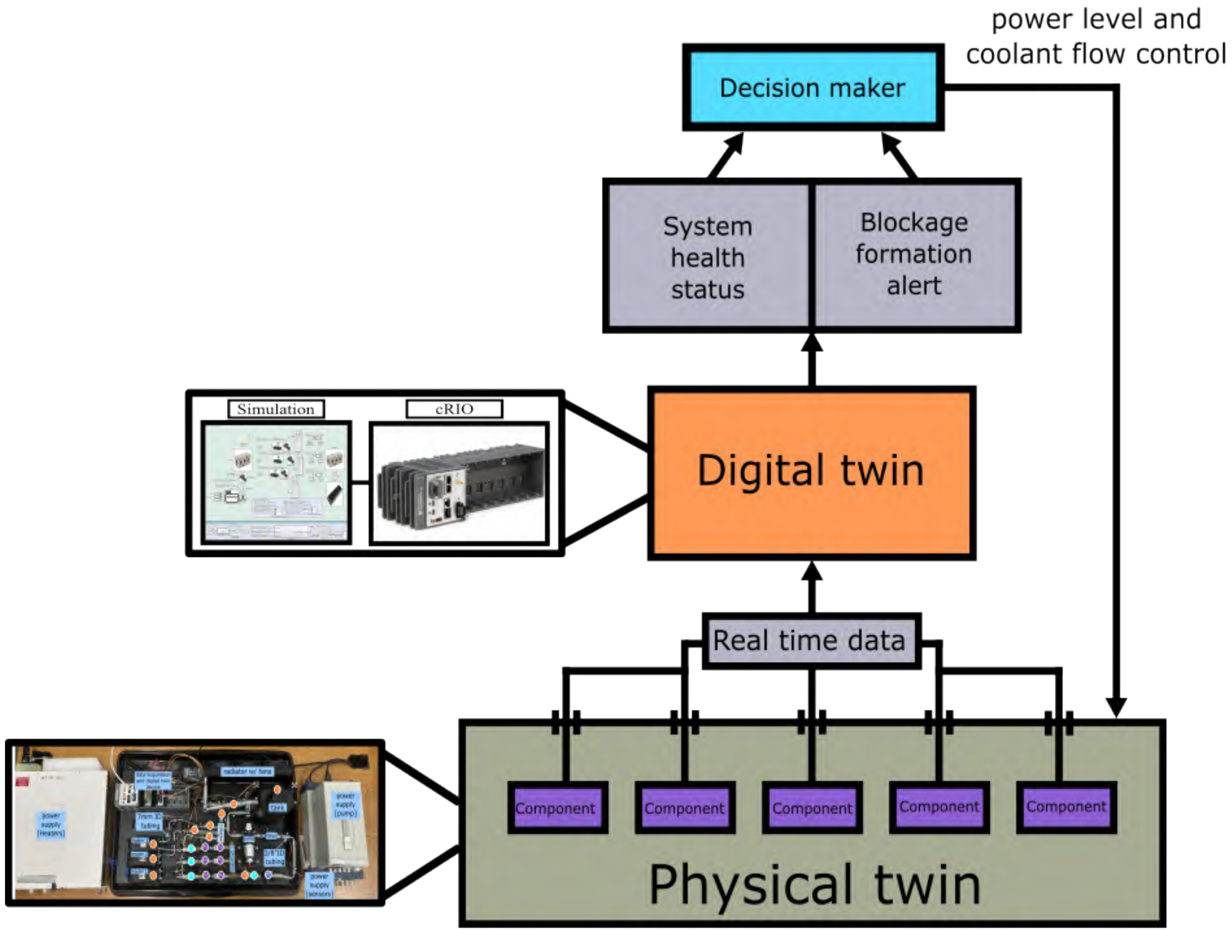
- Real time temp data from physical twin is feed into digital Twin.

Simulation and Blockage Detection:

- Digital twin replicates conditions [waste heat input, coolant flow, etc.]
- Calculates the expected thermal behaviors.
- Determines presence of blockage formation using series of thermal checks and triggers.

Output:

- Informs operator (decision maker) of blockage formation.



INVESTIGATION 2 - SIMSCAPE MODEL – CHARACTERIZATION

Digital Twin Characterization:

- Good characterization of DT with PT and is essential to providing accurate blockage detection.

Importance?

- Dissimilarity between models' thermal behaviors = inaccurate temperature readings and comparisons = unreliable blockage detection.

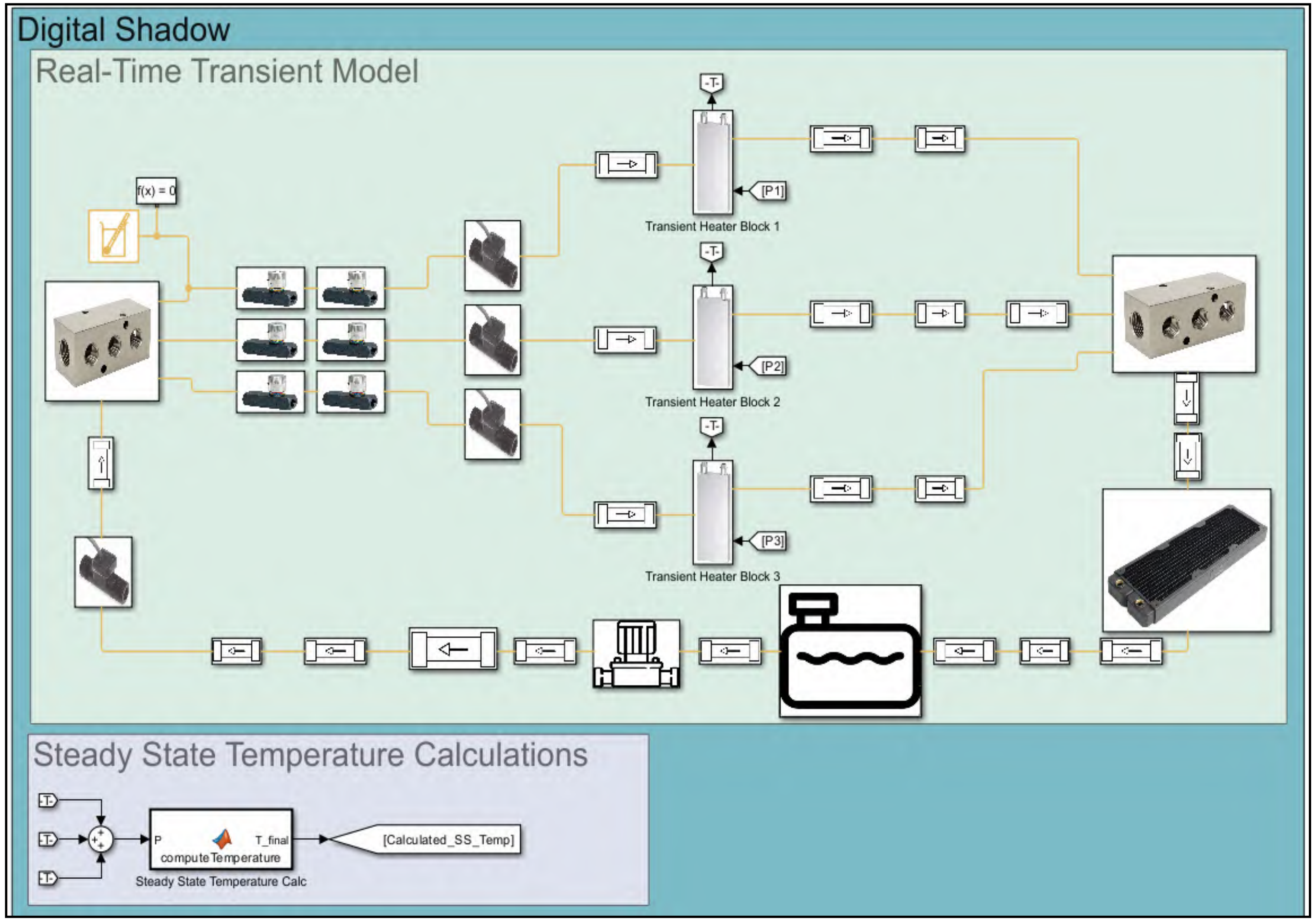
How?

- Characterization values provided by:
  - Manufacturer data sheets.
  - Component measurements.
  - Numerical calculations.

INVESTIGATION 2 - DIGITAL TWIN

Purpose:

- Digital Twin (DT) encompasses the Real-Time Transient Model, and the Steady-State Temperature Calculations module.
- Real-Time Transient Model:
  - Receives the same wattage data as the PT
  - No blockage simulation
  - Characterizes the normal flow parameters of the PT
- Steady-State Temperature Calculations:
  - Receives the same wattage data as the PT
  - Performs thermodynamic calculations



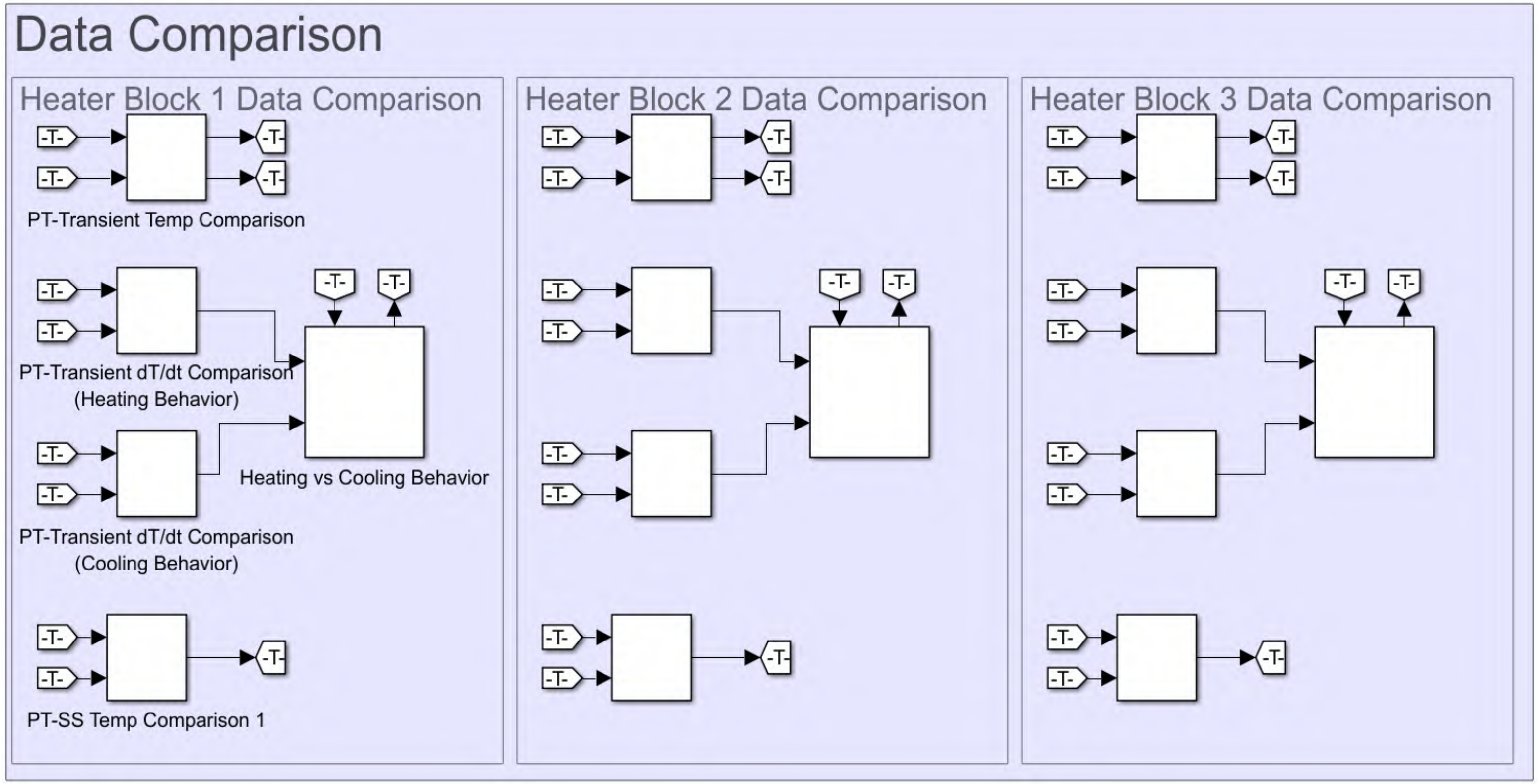
INVESTIGATION 2 - DATA ANALYSIS

Purpose:

- Receives temperature data from PT and DS.

Function:

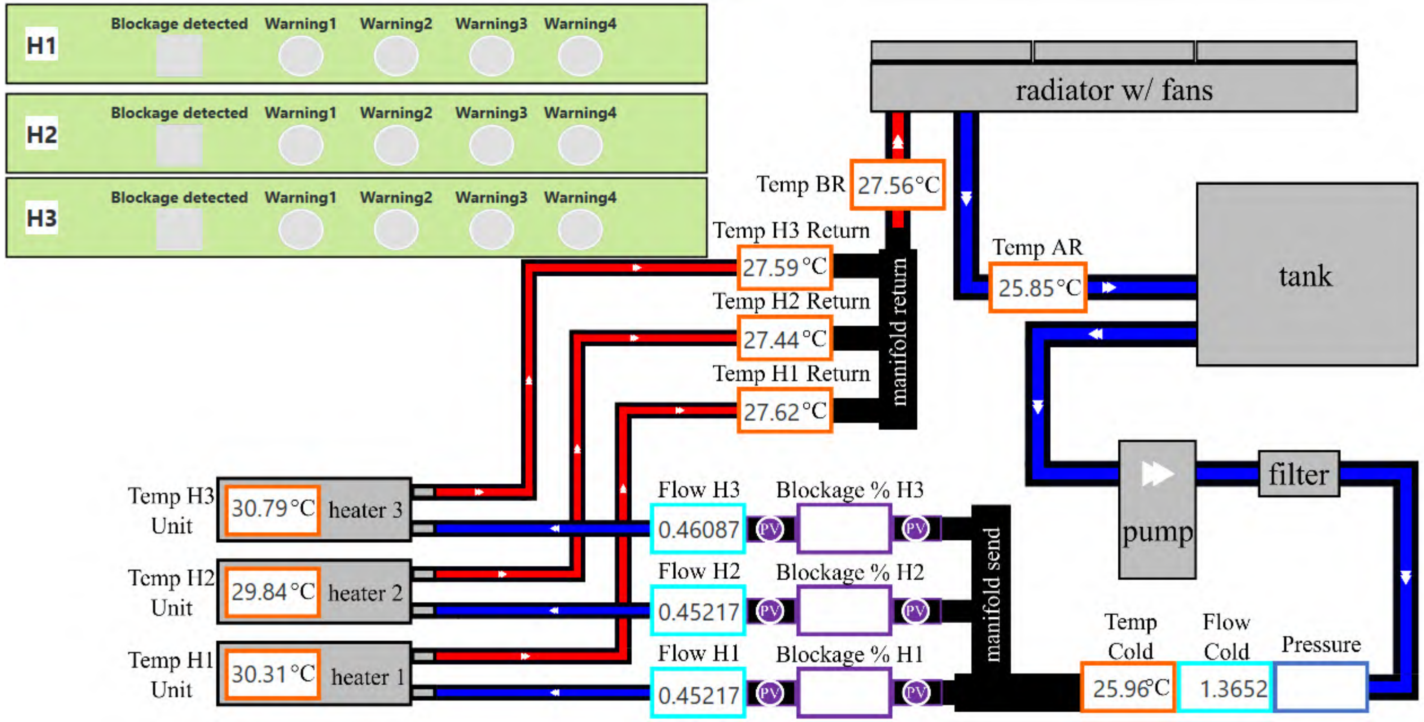
- Compares PT data to idealized data from Transient and SS models.
- Outputs warning signals if the difference between PT and idealized data exceeds threshold.



INVESTIGATION 2 - BDPD MONITORING PANEL

Operation:

- Operator observes conditions within Physical Twin testbed.
- Includes:
  - Coolant thermal conditions throughout system.
  - Coolant flow to heaters.
  - Induced blockage amount in heaters [future feature].
  - Pressure[future feature].
- Overtemperature and blockage formation warning from PT is displayed in panel.



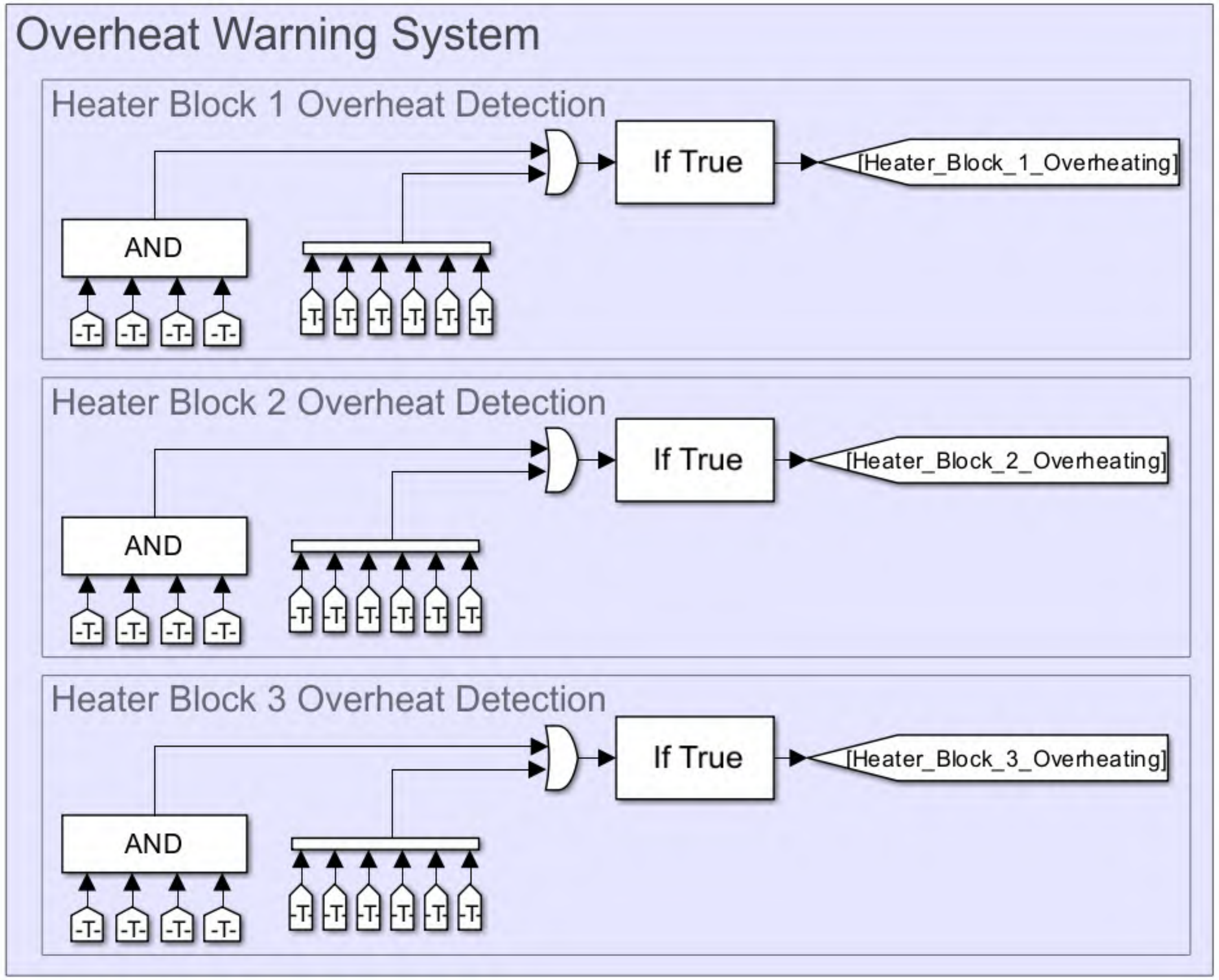
INVESTIGATION 2 - OPERATOR WARNING MODULES

Purpose:

- Receives warnings from data comparison modules.
- Warning trigger signals are grouped and applied to an "AND" logic gate.

Output:

- If all warning signals are received, outputs a blockage detection signal
- Blockage formation warning is sent to Status Block.
- Operator is informed of a blockage formation.



INVESTIGATION 2 - LOAD/BLOCKAGE PROFILES

Heater Block #	Test Profile 1	Test Profile 2	Test Profile 3
1	98.5% Blockage | 125W	0% Blockage | 200W-25W @3600s	80% Blockage | 125W
2	0% Blockage | 125W	98.5% Blockage | 200-25W @3600s	80% Blockage | 125W
3	0% Blockage | 125W	0% Blockage | 200-25W @3600s	0% Blockage | 125W

Purpose:

- The profiles in the table above provide an opportunity to showcase the advantages of this system for blockage detection, in addition to highlighting the optimal operational parameters of the system.

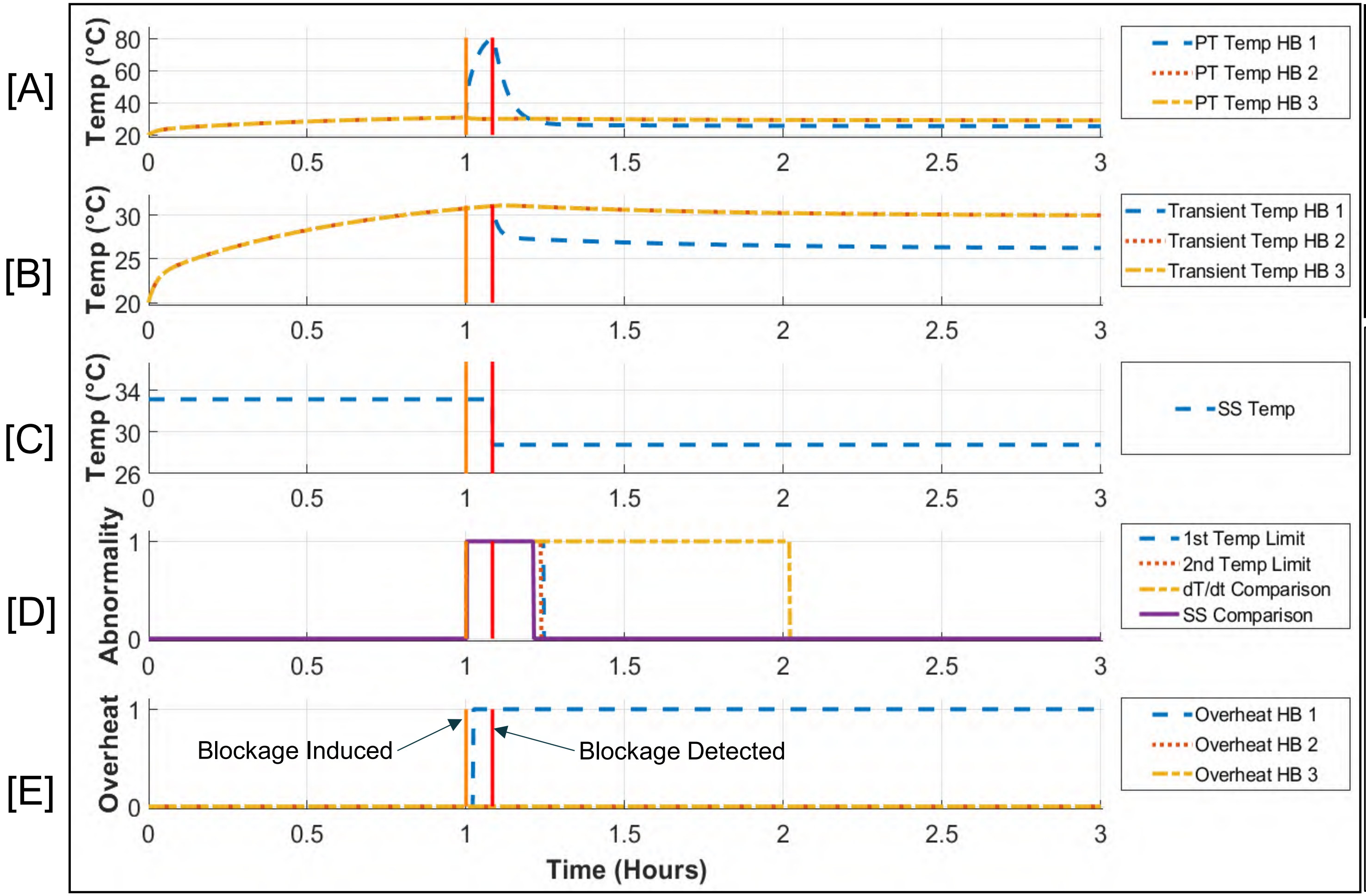
Waste Heat Production:

- Watts denote potential heat loss of a power electronic system due to inefficiencies. Load profiles being shown here correspond to the losses from a 10kW system operating around a 98% efficiency.

Blockage Profiles:

- Test Profile 1 induces a blockage at 3600s (1 hour).
- Test Profile 2 induces a blockage at 4500s (1.25 hours).
- Test Profile 3 induces two blockages simultaneously at 3600s (1 hour).

INVESTIGATION 2 - TEST PROFILE 1



Blockage Profile:

- 98.5% Flow Reduction in HB1 at 3600s.

Load Profile:

- 125 Watts.

Vertical orange line: Blockage Induction.

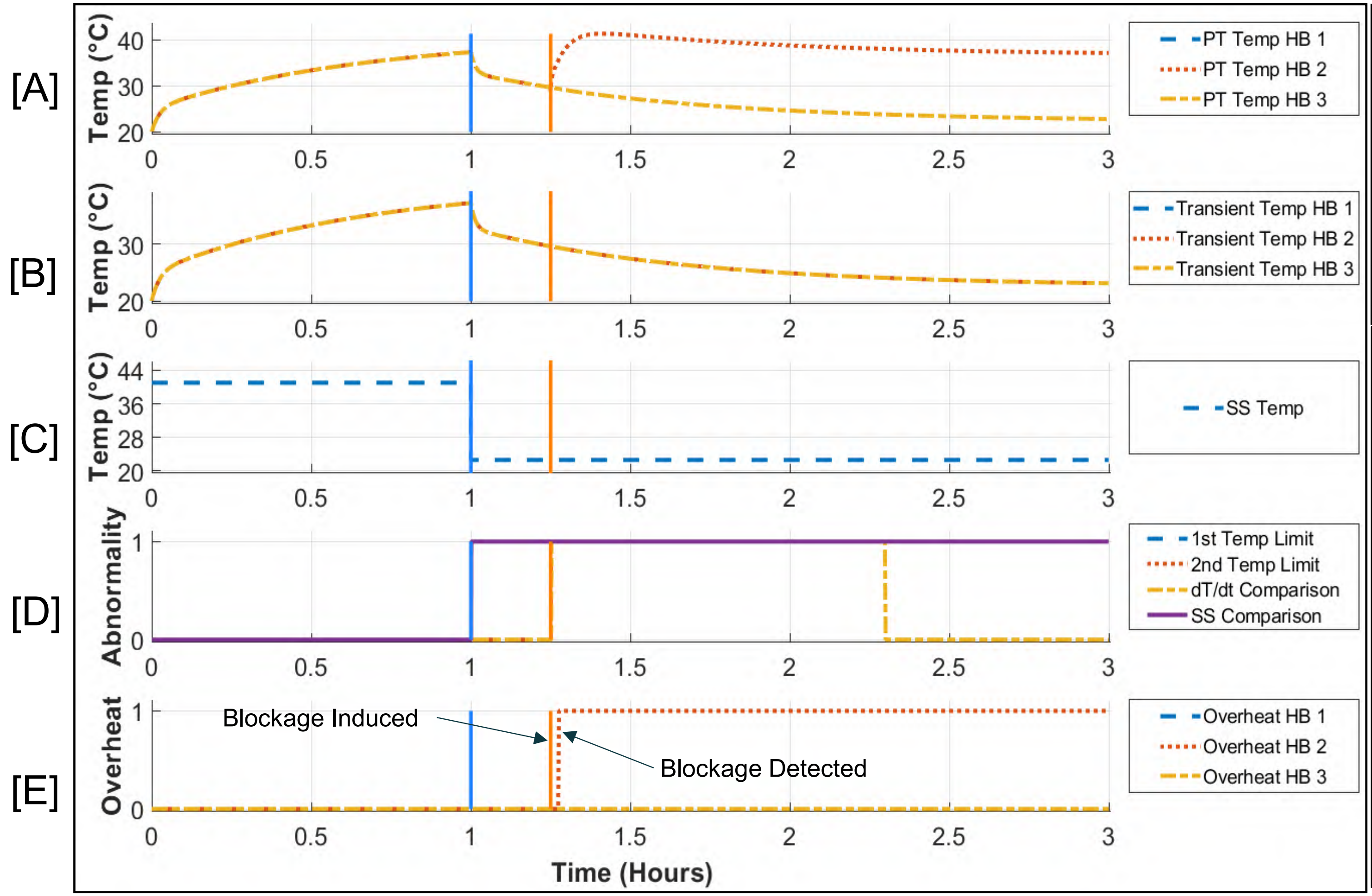
Vertical red line: Power Electronic Shutoff.

Vertical blue line: Planned Wattage Drop.

Time to detect blockage: 1.33 minutes

Time to Power Electronic Failure: 5.00 minutes.

INVESTIGATION 2 - TEST PROFILE 2



Blockage Profile:

- 98.5% Flow Reduction in HB2 at 4500s.

Load Profile:

- 200-25 Watts at 3600s.

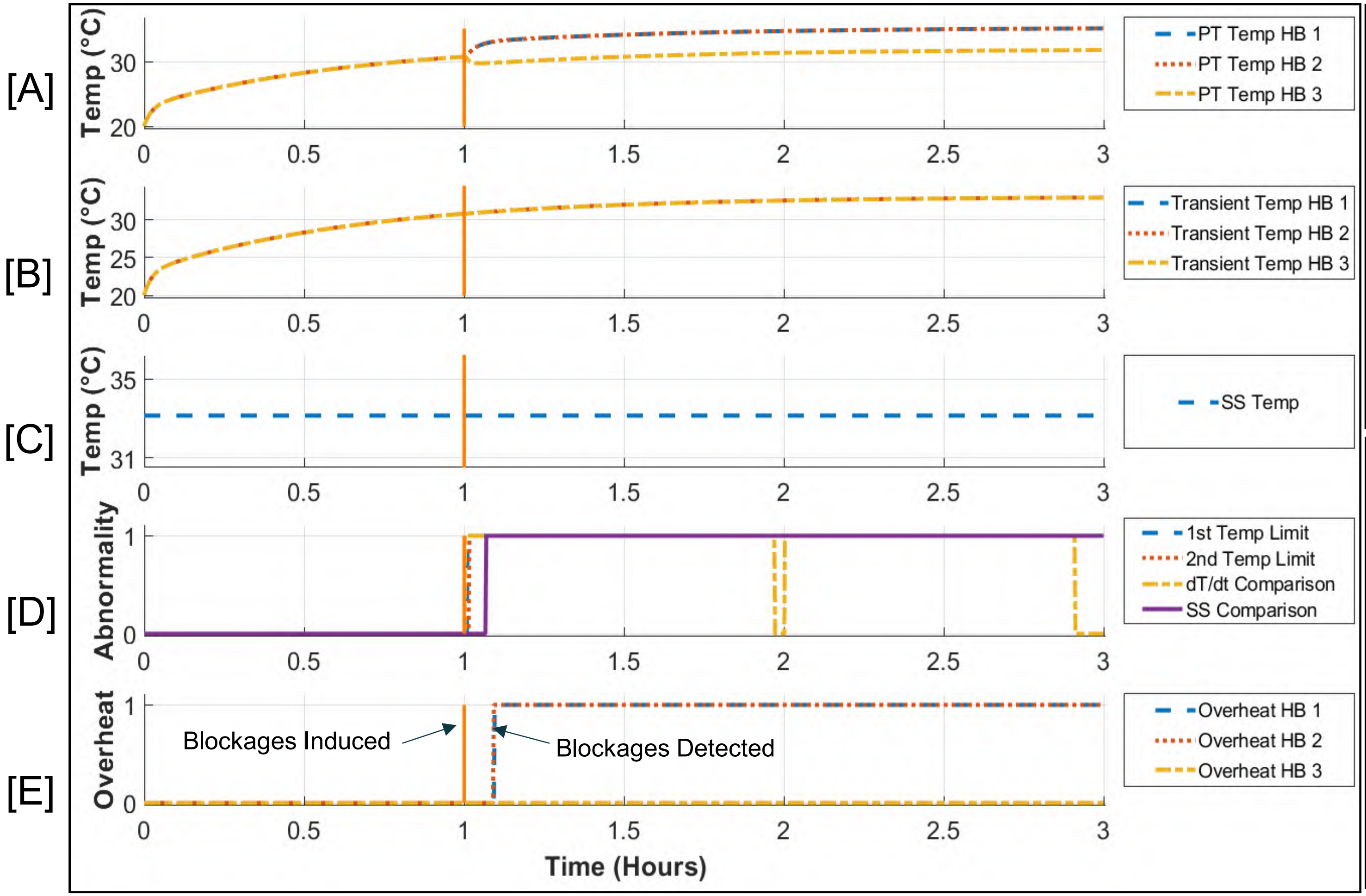
Vertical orange line: Blockage Induction

Vertical red line: Power Electronic Shutoff

Vertical blue line: Planned Wattage Drop

Time to detect blockage: 1.58 minutes

INVESTIGATION 2 - TEST PROFILE 3



Blockage Profile:

- 80% Flow Reduction in HB1 at 3600s.
- Simultaneous 80% Flow Reduction in HB2 at 3600s.

Load Profile:

- 125 Watts.

Vertical orange line: Blockage Induction

Vertical red line: Power Electronic Shutoff

Vertical blue line: Planned Wattage Drop.

Time to detect blockages: 5.66 minutes.

CONCLUSION

Validation of Initial Digital Shadow DS Model:

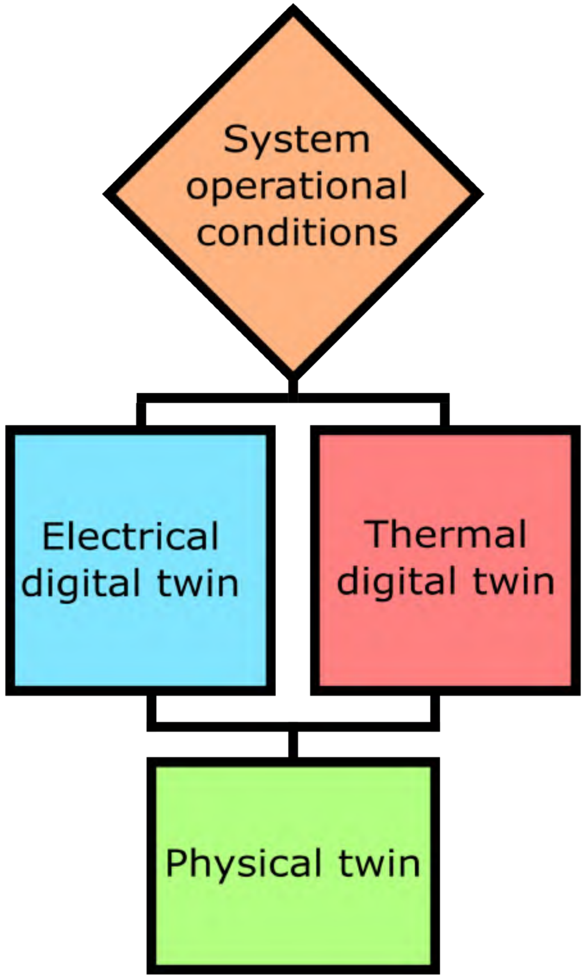
- Results from testing validated thermal digital shadow by replicating cooling system behavior and exploring impacts of coolant blockages.
- Digital shadow provided building block to thermal digital twin.
- DS Aids real-time thermal condition monitoring and effect of blockage formation.

Digital Twin Creation:

- Thermal digital twin simulation with physical twin testbed was created.
- BDPD DT simulation successful in blockage detection during heating and cooling operations under different circumstances.

Future Work:

- Characterize DT with PT.
- Perform experiments to test real life blockage detection ability.
- Inclusion of real time calibration of DT and system aging monitoring.
- Integration of electrical DT to determine if abnormal thermal behavior caused by electrical abnormalities or blockage formation.



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